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CONTROL SYSTEM LAGS AND MAN-MACHINE SYSTEM PERFORMANCE

by F. A. Muckler and R. W. Obermayer

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SUMMARY

This review examines the manual control system literature on the effects of system lags to clarify major conceptual, analytic, and terminological problems. Four control system lags are defined: transmission, exponential, sigmoid, and oscillatory transient delays. The effects of lags on human performance are illustrated through studies of single control lag variables. However, since the interaction of task variables markedly influences tracking performance levels, an analysis of the control lag literature is conducted across the following task variables: system inputs, information sources, operator controls, controlled element and environmental variables. Additionally, the relation between control lags and the procedural variable of transfer of training is discussed.

I. INTRODUCTION

A. Time Delays in Man-Machine Systems

One of the most pervasive phenomena in man-machine systems is time delay in subsystem or component response. On the whole, neither the physical elements nor the human operator respond instantaneously, and in a complex man-machine system the sheer number of elements can result in an appreciable time lag between the initial input to a system and the final system response.

It is well known that the human operator can introduce time delay into sequential system performance. One of the best documented aspects of human behavior is reaction time, the importance of which has been often examined with respect to man-machine systems (see, for example, Ref. 1). Given a set of discrete stimuli, the time delay in human response to one or more of these stimuli can be of the order of magnitude of 0.5 sec or greater. For example, a study completed in 1885 (Ref. 2), showed that disjunctive reaction time increased from 187 ms to 622 ms as the number of stimulus alternatives increased from 1 to 10. Therefore, in the behavior of any human operator, response delays are certainly possible. Delayed response, however, is not a fixed constant of human behavior although it is sometimes theoretically reasonable to assume so (e.g., Ref. 3). In continuous, rapid response, real-time manual control systems, for example, the operator's ability to anticipate system error (based on training and experience) frequency elicits "lead" responses rather than "lag" (e.g. , Refs. 4 and 5).

Indeed, without such lead responses, it is probable that the human would be unable to control adequately this type of system.

Time delays in the response of physical components are usually the result of highly complex physical events. Categorization of these phenomena in terms of their time response alone is neither physically meaningful nor useful, but there are a number of rubrics that cover physical events of possible interest here. Transportation lags, exponential delay, deadtime, deadzones, backlash, hysteresis, etc., are examples. And, although in many cases these phenomena appear in system design unintentionally, they may be purposely introduced for certain relevant design objectives (Ref. 6, pp. 298 and 299 and Ref. 7, pp. 559 and 560).

B. Purpose and Limitations of the Present Report

It is probable in most actual man-machine systems that any final system output delay will be due to both the human operator and machine elements. The purpose of the present report is to consider man-machine system performance where time delays have been deliberately and systematically introduced by variations of the physical control elements of the total man-machine system. Since the appearance of the study by Warrick (Ref. 8), there has been published a growing literature in this problem area which has been commonly termed the effect of "control system lags" on human operator performance. It seems reasonable at this time to evaluate critically this literature in light of some rather obvious and important implications for the design of man-machine systems in general and manual control systems in particular.

However, the report will be limited to four specific physical transformations that purportedly create "control system lags": (1) transmission-type lags; (2) exponential delay; (3) sigmoid delay; and (4) oscillatory transients. Each of these represents a class of physical events that can occur as a result of an operator's output to a physical system (such as a manual control system). Other possibly relevant phenomena will not be examined at this time: delayed-feedback self-tracking (Ref. 9), sampled-data tracking (Ref. 10), discrete, slow-response tasks (Refs. 11, 12 and 13), control deadspace (Ref. 14), and control backlash (Refs. 15 and 16). Further, two major omissions will be noted by the engineering psychologist and the basic psychological specialist. These concern the very extensive literature on the psychological effects of auditory delay (Ref. 17) and visual feedback delay (Ref. 18). These exclusions have been deliberate in order to concentrate on the 17 studies that constitute the core literature of the subject, hopefully to clarify a number of major conceptual, analytic, and terminological problems.

C. A Preliminary Definition

In quite gross oversimplification, the time sequence of operator behavior, is somewhat as follows in most crew station continuous performance tasks. The operator receives stimulus inputs from a display console. He in turn makes some control input to the rest of the system. The system resultant of his control movement is then displayed in successive stimulus signals from the display console, and his subsequent behavior is presumably based on these sequential, feedback, stimulus inputs.

Definition: The time delay between the original stimulus signal and the successive stimulus signals that result from his control movements is the delay of basic interest to the operator whether or not that delay is caused by the operator or by physical subsystem elements. When the delay is caused by control system element responses, the stimulus signal delay is said to be caused by "control system lags."

Two points need to be made clear immediately. First, all sequential stimulus signals are "delayed" in the sense that they must follow each other in time. The question of importance here: is the effect of stimulus delay caused by certain control system events? It has been frequently assumed that any delay is deleterious to human performance, that immediate knowledge of system response is desirable. The concept of display quickening (Refs. 19, 20, and 21) in fact requires that anticipatory information, through feed-forward loops, be provided to compensate for control system lags. Specific exceptions to this generalized concept will be noted in the present literature.

Second, the definition is clearly a psychological one, and pertains to the input-output time variables of the human operator alone. It is, therefore, incomplete with respect to the specification of the total man-machine system. Yet, this definition is essential for understanding the technical motivation for the core experimental studies in this literature. All these studies have in common the stated operational procedure that successive stimulus signals are assumed to be delayed due to a variety of physical causes. It seems reasonable, therefore, to orient the discussion initially around stimulus delay regardless of the causal variables operating, on the assumption that, from the point of view of the operator, it is the stimulus-response delay that is of paramount importance. As will be seen, both of these assumptions are open to question.

II. CONTROL SYSTEM LAGS: SINGLE VARIABLES

A. The Physical Events: Step Functional Input

As defined, we are concerned here with four particular physical transformations that result in control system lags: (1) transmission-type lags, (2) exponential delay, (3), sigmoid delay, and (4) oscillatory transients. At this point, it is desirable to specify more precisely the exact nature of these responses, both graphically and by equation. In the literature, the response definition is always made with respect to a step-function input signal to the control system.

A step function input consists of an instantaneous rise from a steady-state zero level to another steady-state level, and therefore serves as an excellent (i.e., simple) input for the study of the response of systems with lags. Assuming such a step-function input, Fig. 1 shows the response of a hypothetical control system with each of the four types of "lags." In each case, a characteristic equation describes the system response:

$$\theta(t - \tau) = C(t) \qquad \text{Transmission} \qquad (1)$$

$$\dot{\theta}(t) + \theta(t) = C(t) \qquad \text{Exponential} \qquad (2)$$

$$\ddot{\theta}(t) + 4.3\,\dot{\theta}(t) + 4.62\,\theta(t) = C(t) \qquad \text{Sigmoid} \qquad (3)$$

$$\ddot{\theta}(t) + 0.248\,\dot{\theta}(t) + 1.542\,\theta(t) = C(t) \qquad \text{Oscillatory} \qquad (4)$$

and "delay" or "lag" is defined as the time (τ) at which the response exceeds 63% of the required final output level based on the magnitude of the step-function input; in short, the time constant. The time history functions plotted in Fig. 1 are specifically computed with parameters such that they all agree at the end of one "delay-time," but it may be seen that they will agree again only after sufficient time has elapsed so that all have settled down to the same steady-state level. In the oscillatory case, in particular, this may be a very long time period.

As indicated in Fig. 1, for the exponential "lag" the physical response is, in fact, immediate and starts from zero. In contrast, with sigmoid and oscillatory dynamics, both position and rate of movement are initially zero. The first response to a step input is slower for the sigmoid and oscillatory cases, as compared with the exponential response, but the later response for both is more rapid. The sigmoid lag and the oscillatory lag are both cases of second order dynamics, and, of course, a family of responses could be shown in Fig. 1 including the sigmoid response (equal roots) and the relatively undamped oscillatory response (complex roots). Finally, it should be noted that the physical response of a given system to a particular input is not always typical of the response for other input functions. However, the step function is simple, and is classical in the sense that it has served as the basis for the definition of control system lags in all the studies performed to date.

B. Transmission-Type Lags

Tracking performance as a function of transmission-type lags has been investigated by Warrick (Ref. 8) who used a single-dimension compensatory

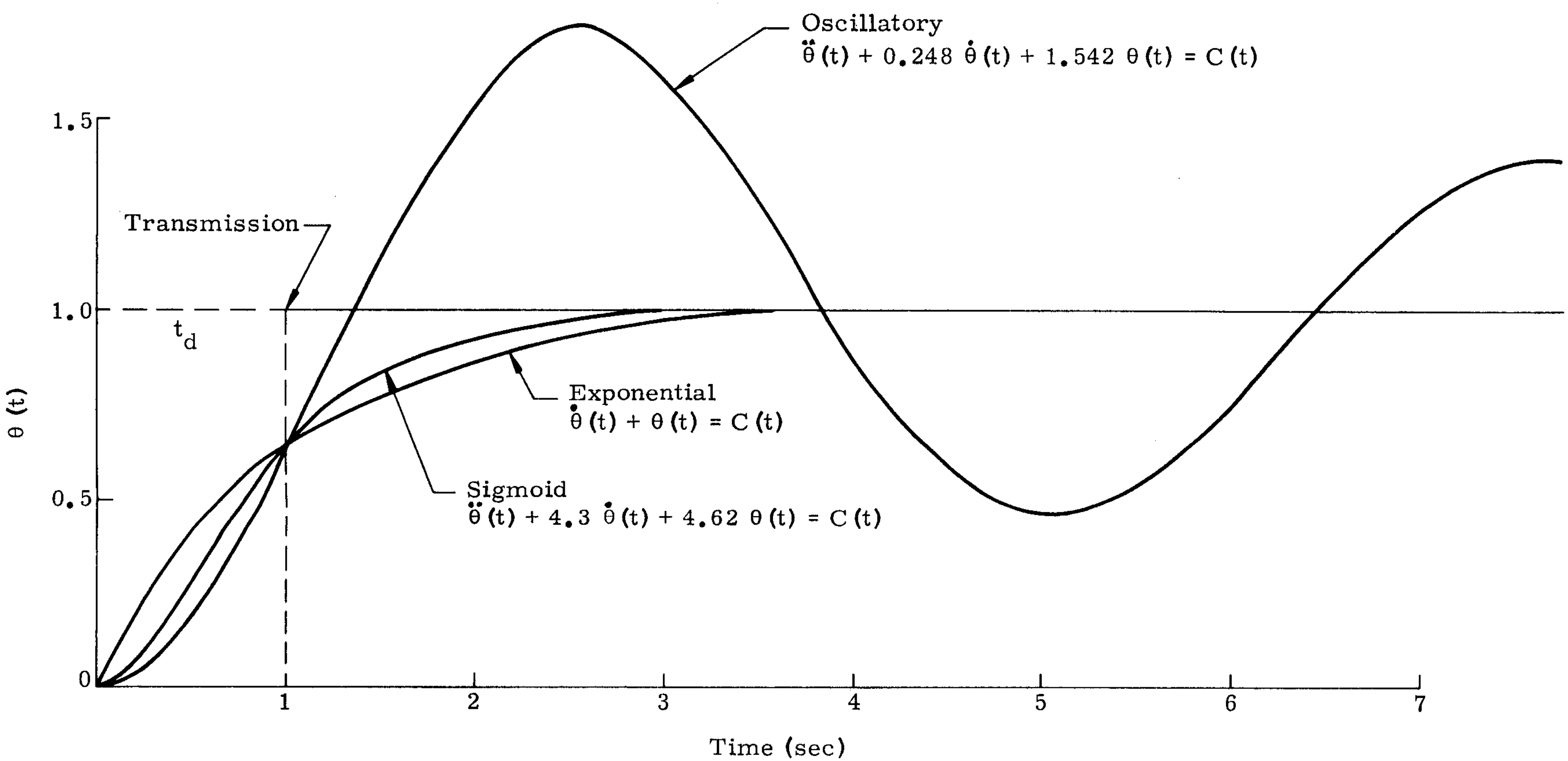

Fig. 1. "Control System Lags" Responses to a Step Function Input

task with a knob control. The display device was a d-c recording oscillograph presenting a complex forcing function based on the combination of two basic frequencies of 6 and 30 cycles per minute. The operator's task was to null any deviations of the pen from a line on the moving graph paper. Lag was introduced by a somewhat unique method involving adjustments of the stimulus slit on the oscillograph; five delays were used, 0, 40, 80, 160 and 320 ms.

Warrick found that there was an inverse linear relationship between the logarithm of time on target and control lag. The results are shown in Fig. 2. His data were sufficiently regular to be expressed by the following equation:

$$\log Y = a + bX \tag{5}$$

where

Y = time on target

X = lag between control and display

a = constant

b = constant

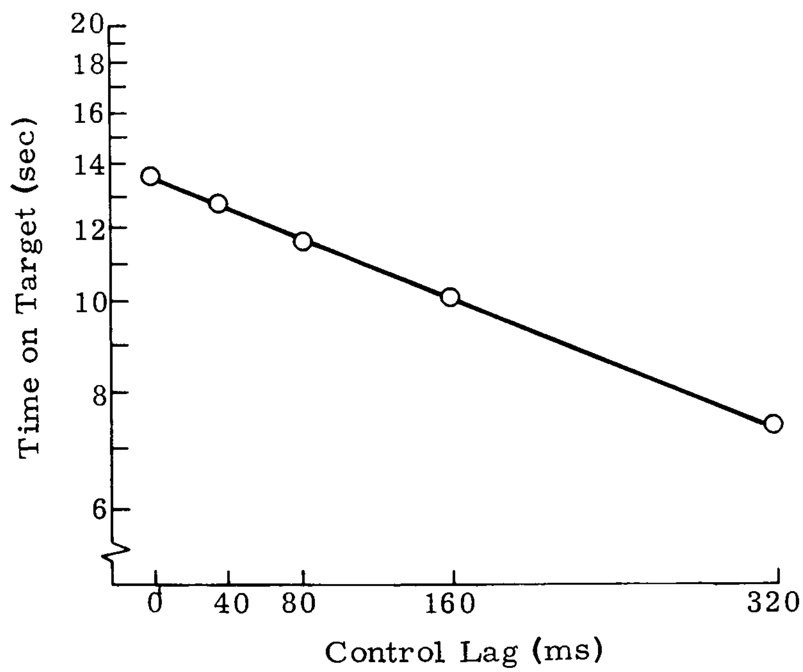

Fig. 2. The Effect of Transmission-Type Control Lags on Tracking Performance (ref 8, p 11)

The constant b is seen to be the slope of the line; it must be negative so that Y decreases as X increases. According to Warrick, the constant a can be determined from the mean time on target of the zero delay interval. Furthermore, as the system is changed to allow greater or lesser zero delay time on target scores a is said to change without affecting b. Warrick tested this experimentally by changing the possible base score, and he found that a could indeed be varied without affecting b.

Of particular importance is the 40-ms delay condition. According to work reported by Biel and Warrick (Ref. 22), the absolute stimulus threshold for this type of lag is about 60 ms. If this is the case, then the 40-ms delay was not perceived by the subject. Nevertheless, as Fig. 2 shows, tracking performance for the 40-ms condition was poorer when compared with the zero delay condition. This fact is not consistent with the assumption stated in Section I-A, namely that the important variable from the operator's point of view is successive time delay of stimulus signals. In this particular condition the time delay is not perceivable, and hence the prediction should be that there would be no performance degradation.

C. Exponential Delay

The two original studies on the effect of exponential delay were those of Levine (Ref. 23) and Warrick (Ref. 24). Levine used a single-dimension compensatory tracking task. The forcing function was derived from the sum of three sine waves with frequencies of 3, 5 and 11 cpm (cycles per minute). A knob-type control was provided for the operator. Eight exponential delay times were introduced: 0.015, 0.06, 0.150, 0.6, 0.9, 1.5, 2.1 and 2.7 sec.

In general, increasing the exponential delay was found to produce a linear decrease in performance. The pooled time on target data from Levine's study (Ref. 23, p 13) is shown in Fig. 3. An equation of the best-fit straight line is as follows:

$$Y = 19.45 - 2.26X \qquad (6)$$

where

Y = time on target in seconds

X = exponential delay time constant in seconds.

Levine felt that a linear function was reasonable for delays greater than 0.150 sec but raised the possibility that for delays less than that value the shape of the function might change. An important secondary finding was that two subjects from the total sample (N = 12) deviated in their individual performances from this linear relationship. Subject variability must always be closely examined

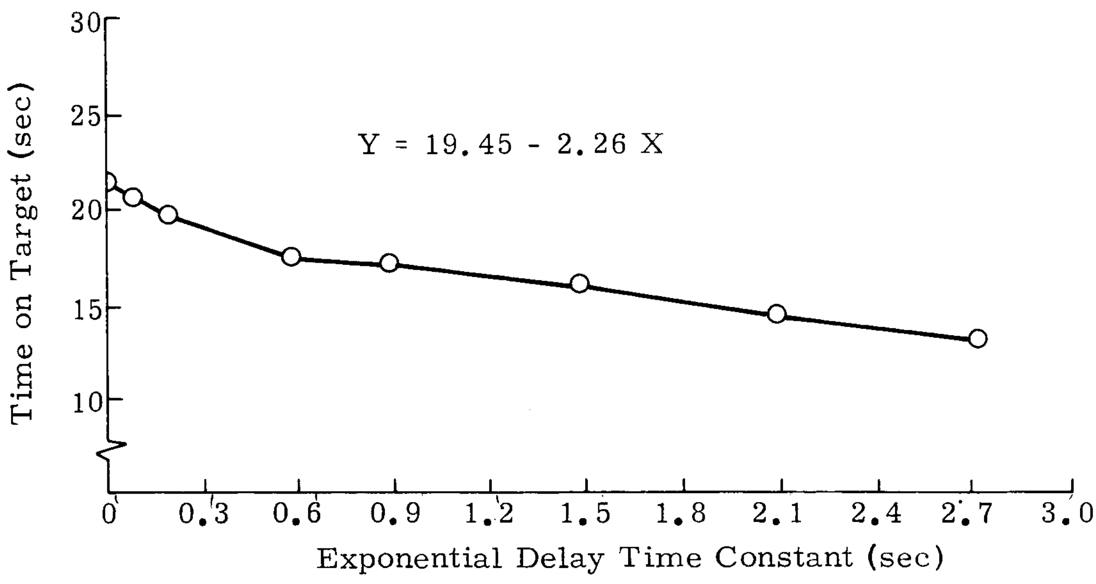

Fig. 3. The Effect of Exponential Control Lags on Tracking Performance (ref 23, p 13)

in these types of manual control studies; in some cases, entirely opposed individual subject functions can be obtained varying significantly from the sample means (e.g., Ref. 25).

The Warrick study (Ref. 24) used exponential time delays of 0, 40, 120, 360, and 1000 ms. The task involved compensatory tracking, with a rotary control knob, but the forcing function was discrete display input step displacements 3, 6, 9, 12, and 15 mm left and right of the center display mark. The task emphasis, therefore, was on subject speed and accuracy of repositioning the display target needle after it had been displaced; in the strict sense, this was, of course, not continuous tracking. Four performance measures were recorded: (1) slewing time: from initial display signal movement to initial return to center; (2) acquisition time: from initial display movement until stable repositioning on center for three seconds; (3) settling time: slewing time subtracted from acquisition time; and (4) excessive center crossings: number of center crossings in excess of one per trial cumulated over 20 training trials.

Table 1 shows the mean values obtained for these four measures based on a subject sample size of 20 subjects.

TABLE 1

Mean Response Scores, Warrick Exponential Lag Study (Ref. 24)

Response Measure	Exponential Lag (ms)				
	0	40	120	360	1000
Acquisition time (sec)	0.807	0.897	0.984	1.307	1.835
Slewing time (sec)	0.725	0.788	0.873	1.132	1.439
Settling time (sec)	0.082	0.108	0.111	0.176	0.396
Number excessive center cross.	5.40	5.05	6.15	7.15	9.40

In general, increased control lag results in an increase in all performance measures. Statistical evaluation demonstrated the effect to be significant (1% level) for acquisition time and slewing time, but not for settling time or excessive center crossings. Subject variability was low for acquisition time and slewing time, and relatively much higher for the other two measures.

The relationship between settling time and control lag suggests a possible linear function, but such was not the case for acquisition time and control lag or slewing time and control lag (see Table 1). Warrick strongly suggests that the subject is at least partially compensating for the physical lag. Slewing times were shown to be considerably less than those predicted if the subject had made no change in his control behavior with increased lag (Ref. 24, p. 10).

The scores suggest that the effect of control lag is particularly apparent with respect to settling on the display target. Comparing 0- and 1000-ms lag scores, acquisition time increased 130%, slewing time increased 98%, excessive center crossings increased 74%, but settling time increased 383%. Thus, as Warrick (Ref. 24, p. 11) notes: ". . . it is particularly difficult for the operator to make the final precise adjustments of the pointer."

The Levine study (Ref. 23) and the Warrick study are not directly comparable since they impose quite different task requirements on the operator. Levine required continuous compensatory tracking while Warrick used discrete repositioning of a display marker. However, in both cases, the effect of introducing control lags of the exponential type was to reduce considerably performance levels as compared with the zero lag condition.

D. Sigmoid Delay

Two extremely valuable studies on the effect of sigmoid delay have been reported in the literature by Conklin (Refs. 26 and 27). These experiments compare the effects of both exponential and sigmoid delays as a function of the type of tracking task (pursuit versus compensatory) and variations in the forcing function frequency components. Since these studies are primarily concerned with interaction effects, full discussion of them will be withheld until the problem of interaction effects is treated in Section III.

However, to illustrate the effect of sigmoidal lag, a single comparison between exponential and sigmoidal lags may be given (Ref. 26 p. 265). In this case, the following conditions held: simple sine wave forcing function of π rad/sec; compensator tracking task; exponential and sigmoid delays of 0, 0.25, 1.0, 4.0, and 16.0 sec time constants.

Figure 4 shows the comparative effect of exponential and sigmoid delays on tracking performance. The dependent variable--RMS ratio score--is the ratio

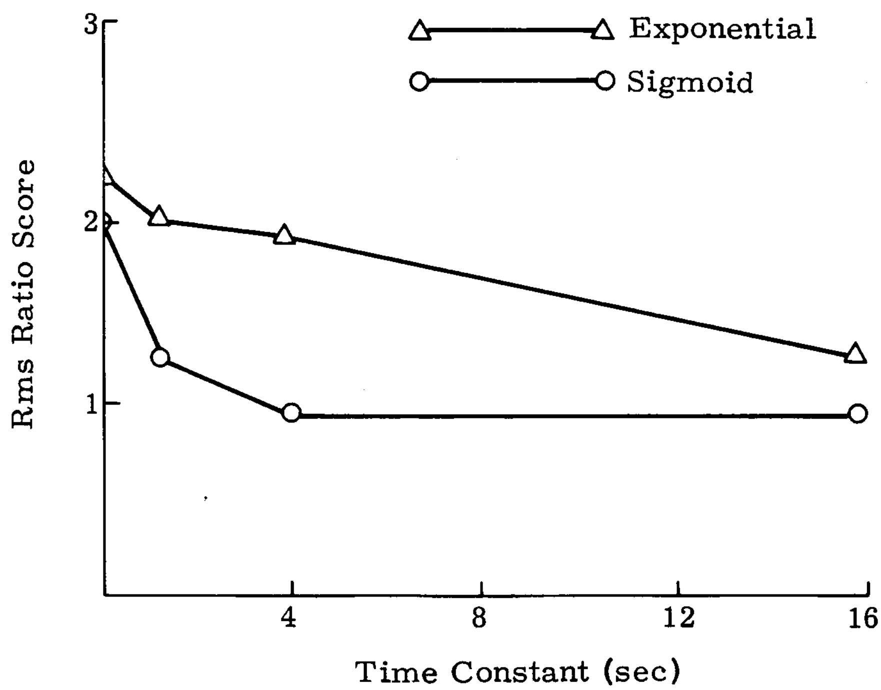

Fig. 4. Comparison of the Effects of Exponential and Sigmoid Lags on Tracking Performance (ref 26, p 265)

of RMS display signal error to the operator's output RMS. A ratio score of 1.00 is "chance" performance; scores higher than 1.00 indicate error reduction by the operator. It is interesting that, in Fig. 4, some levels of performance with the sigmoid lags are below that which might have been achieved if the operator had done nothing at all. At any rate, the trend is clearly toward reduced performance levels for both types of lags as the time constant is increased.

E. Oscillatory Transients

The oscillatory transient condition shown in Fig. 1 represents a far more difficult control problem for the human operator. Depending upon the particular system, it is characteristic that such responses stabilize in time, but it is not uncommon to encounter systems that are neutrally stable or even unstable. That is, the amplitude of the oscillation may increase instead of being damped. The operator must then deal not only with system "lag," but with system stabilization as well.

A number of studies have been reported on the effects of short time constant (Refs. 25 and 28) and long time constant (Refs. 28 and 29) oscillatory control system transients. A simple demonstration of the effect of stable, short time constant, oscillatory transients has been given by Muckler and Obermayer (Ref. 28). Single-dimension compensatory tracking was used. The forcing function was a simple sine wave of 6 cpm. The tracker's control output (aircraft joystick) generated oscillatory transients varying in period values of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 sec. The time to damp to half amplitude (with step input) was 1.5 sec for all six period values.

Figure 5 shows performance (in time on target scores) as a function of the period values. In this case, performance levels increase as the transient period increases. At the very rapid short period values (e.g., 1.0 and 1.5 sec), the system response is difficult for the operator to control. Additional studies suggest that performance levels are maintained at a high level until the period values reach 71 sec, or, rather, somewhere between 35 and 71 sec (Ref. 28, p. 27).

F. "Display" and "Control" Lags

Under the preliminary definition given in Section I-C, the critical factor in performance levels with control system lags was said to be the time delay between successive input signals to the tracker. If this definition is correct, then pure input delay time is the critical variable, no matter how this delay is produced within the system itself. However, the study of Garvey, Sweeney, and Birmingham (Ref. 30) suggests that this is not correct.

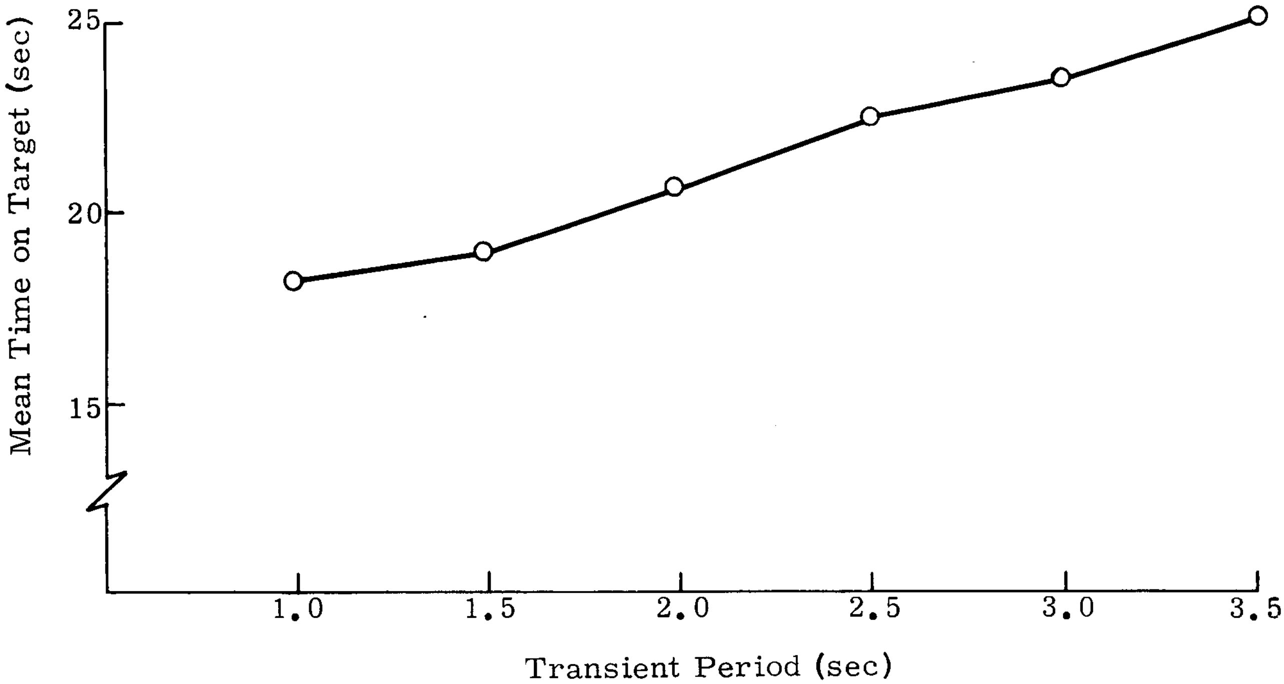

Fig. 5. The Effect of Oscillatory Control System Lags on Tracking Performance (ref 28, p 24)

Using a compensatory tracking task, with a position control joystick, a forcing function combined from 3-, 5-, and 11-cpm sine waves, sigmoid delays were inserted either after the control output ("control lags") or before the display input ("display lags"). If the definition given in Section I-C is adequate, there should be no differential effect on operator performance. Figure 6 shows this is clearly not the case. The effect of "display lags" is markedly, and significantly, greater than that of "control lags." Further, in distinction to other studies cited previously, the trend of "control lag" performance levels was found not to be statistically significant.

An explanation of this finding is not easy to obtain. As the authors note (Ref. 30, p. 10), the trackers were unaware of the position of the filter creating "display" or "control" lags. One possible distinction lies in the potential effect of the "control lag" filter in reducing the "noise" component of the tracker's output. Consideration of this factor is difficult to evaluate without detailed knowledge concerning the microstructure of the operator's output to the controlled element. Power spectra of the precise outputs of the operators would be of interest in comparing the two conditions.

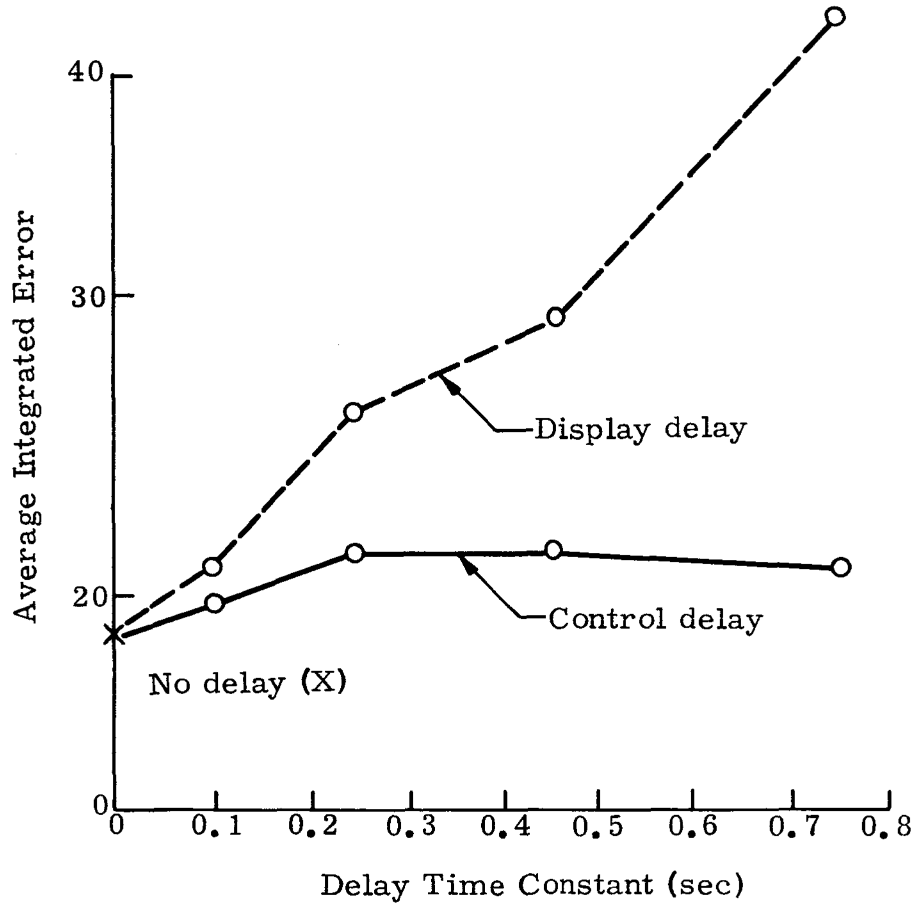

Fig. 6. Differential Effect of "Display Lag" and "Control Lag" on Tracking Performance (ref 30, p 9)

G. Summary and Conclusions

In this section, an attempt has been made to illustrate the kinds of variables that have constituted the general study of the effect of control system lags on human tracking performance. It has been shown that the introduction of transmission, exponential, and sigmoid delays does reduce the efficiency of human tracking performance with the magnitude of the effect increasing as the delay is increased. On the other hand, oscillatory transients create a quite different type of effect. Finally, the point at which a delay is inserted in the total control system loop was shown to affect differentially tracking performance.

However, these studies must be considered as demonstration phenomena of what can happen in tracking under certain specified, and limited, conditions. The specification of control system lags alone is not adequate to define a control system of which the human is an element. It has been clearly demonstrated that the interaction of task variables markedly influences human performance levels in tracking (e.g., Refs. 31 and 32). The following section will examine the literature with respect to task variable interaction and tracking performance.

III. CONTROL SYSTEM LAGS: INTERACTION EFFECTS

A. Task Variable Interaction

One of the most difficult factors in the study of manual control systems is the sensitivity of the human operator to changes in many of the system elements. In fact, a major problem is to discover configurations in which operator performance is invariant. Higher-order interaction effects must be expected in manual control, and, at present, there is no formal theory to account for such interactions. Figure 7 is a generalized schematic accounting for some of the major task variables, that have been demonstrated to affect performance in manual control although it is certainly not exhaustive. Following Adams (Ref. 4), a distinction is made between "task variables" representing variables in the machine system elements and "procedural variables" pertaining to the human in particular such as training conditions, transfer of training, and motivation.

The purpose of the present section is to examine those studies of the effect of control system lags where other task variables in addition to control system lags were systematically changed. Based on Fig. 7, the following task variables are of interest.

System inputs. In the usual hardware system, the input functions are provided by sensor inputs and/or computer-generated command inputs. In the laboratory, common practice is to introduce aribitrary forcing function inputs ranging in complexity from simple sine waves to random noise functions.

Information sources. In hardware systems, the information sources, and hence the associated displays, are usually numerous and complex due simply to the fact that the human's operational task is a complex one. In the laboratory, the task is usually considerably simpler with a major distinction being either compensatory or pursuit display.

Operator controls. A large literature has developed on the physical nature of the operator's control alone (cf. Ref. 33). With the exception of the study of Gibbs (Ref. 34), to be discussed later, the type of physical control has not been of interest in the control system lag literature.

However, perhaps the most important task variable investigated in interaction with control system lags has been that of "control gain," operationally referring to the systematic amplification of the operator's control output. As Gibbs (Ref. 35) has remarked, the term "gain" has had a variety of usages in the literature. It is possible to refer to "control gain," "display gain," "system gain," "control/display ratio," "display/control ratio," "visual display scale," "arm control scale," "gear ratio," "stiffness," and "sensitivity." Operationally, all of these refer to display-control gain insofar as the operator is concerned; yet, for each study the specific "gain" technique will have to be specified.

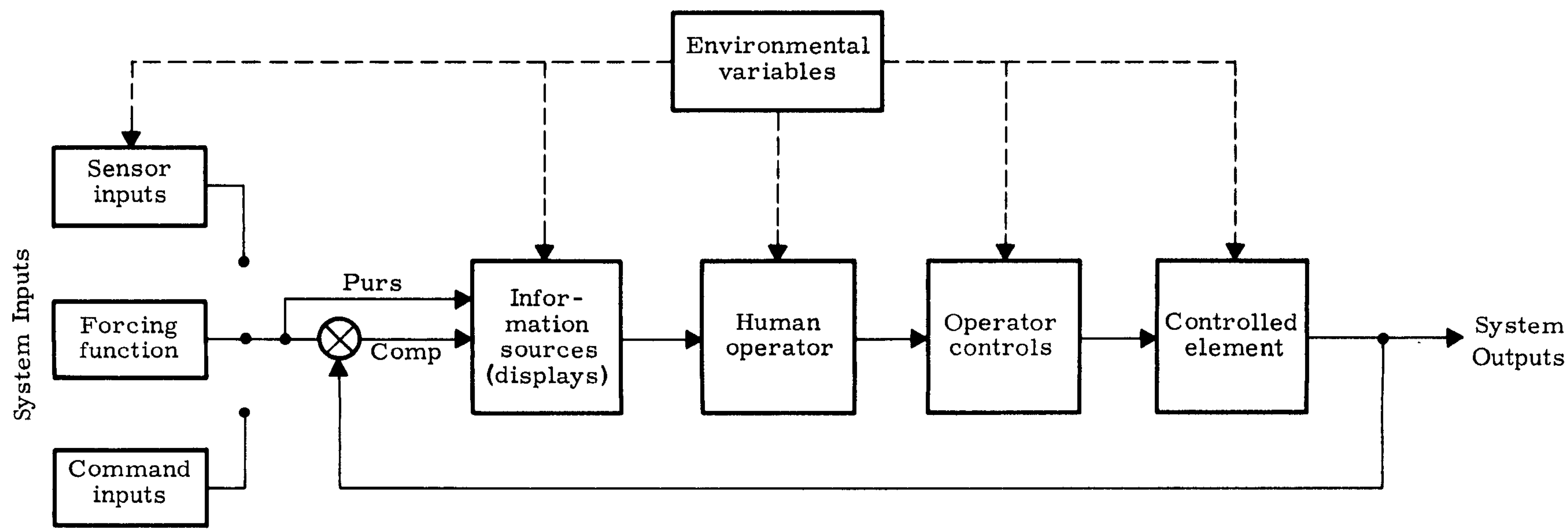

Fig. 7. Generalized Schematic of Critical Task Variables in a Manual Control System

Controlled element. As described in Section II-a, the present concern is with four transformations of the controlled element with respect to transmission, exponential, sigmoid, and oscillatory responses to a step function input (Fig. 1).

Environmental variables. In practice, environmental variables (e.g., acceleration, noise, vibration, etc.) may affect the entire system (Fig. 7). As will be noted, Kaehler (Ref. 36) has studied the dual effect of acceleration loads and exponential lags.

In the studies to be reviewed in this section, one or more task variables have been studied experimentally with various types of control system lags. However, there have been no published interaction studies with control system lags of the transmission type.

B. Exponential Lags

1. Rockway (Ref. 37). Given increasing exponential delay, Levine's (Ref. 23) data have been cited to show a linear decrease in performance with increasing lag. Using exponential time delays of 0.3, 0.6, 1.5, and 3.0 sec, Rockway also varied gain by using four control/display (C/D) ratios: 1:3, 1:6, 1:15, and 1:30. Specifically, the C/D ratio is defined as: given 1° control deflection, the display index moves 3/16, 6/16, 15/16, or 30/16 in. Further, the relationship between control deflection and display movement was linear. Thus, for a C/D ratio of 1:3, a 1° stick deflection moved the display index 3/16 in.; a 2° deflection, 6/16 in.; a 3° deflection, 9/16 in.; and the maximum stick deflection of 11, 33/16 in. Under these conditions, the C/D ratio of 1:3 is essentially a low gain response while the C/D ratio of 1:30 is a high gain response.

Figure 8 demonstrates clearly the interaction effect between exponential time constant and C/D ratio. The low gain condition (C/D ratio = 1:3) produces the characteristic decreasing performance levels with increasing time constant (see, Fig. 3). With the high gain condition (C/D ratio = 1:30), performance improves as the exponential time constant is increased. Most important, the intermediate gain conditions (C/D ratio = 1:6 and C/D ratio = 1:15) illustrate both rising and falling trends as a function of the time constant.

2. Gibbs (Ref. 34). This study was designed to compare experimentally (1) positional versus velocity control systems, (2) exponential lags, (3) gain, and (4) relative effectiveness of thumb, hand, and forearm in making corrective repositioning of a visual indicator. The task, therefore, was not tracking in the usual sense, but was similar to that of Warrick (Ref. 24) previously cited.

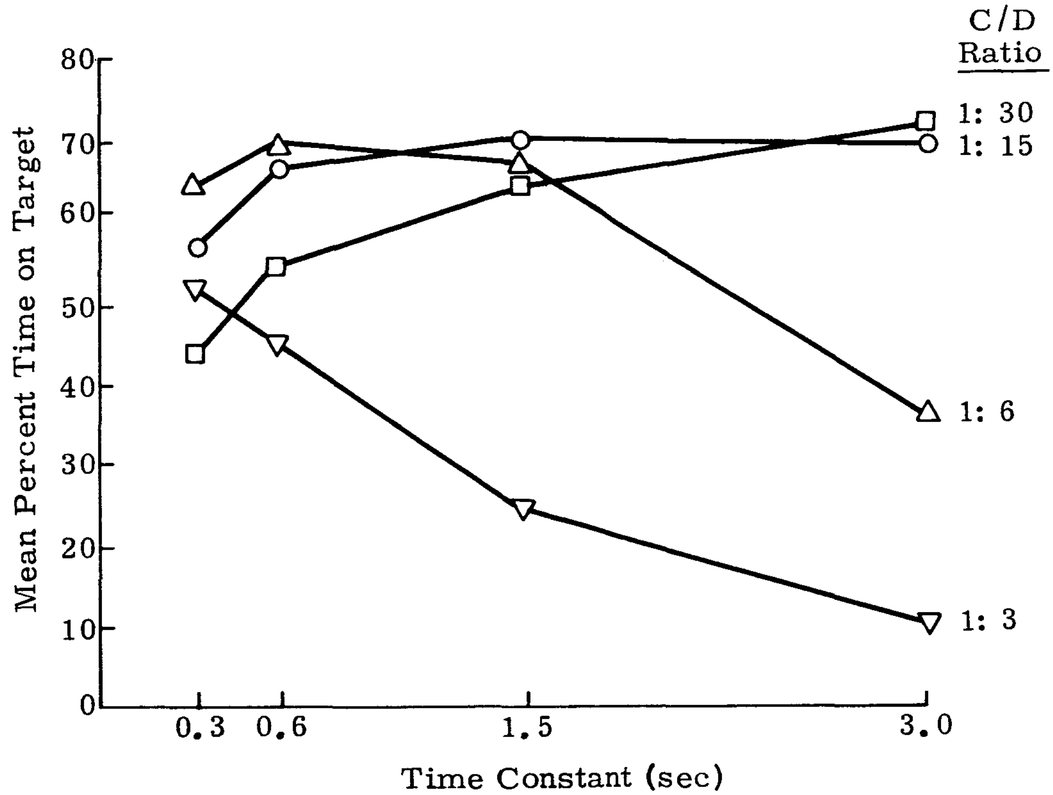

Fig. 8. The Interaction of Control/Display Ratio and Exponential Lag in Tracking Performance (ref 37, pp 9 and 10)

Position control. With a position control system, exponential lags of 0, 0.08, 0.20, 0.50, and 2.00 sec were introduced. Six values of gain were used: 0.15, 0.20, 0.30, 0.40, 0.50 and 0.90 referring to the angular movement of the display index relative to the corresponding angular movement of the appropriate control. Thus, a gain of 0.15 specifies that a 1-rad joystick movement moved the display index an angle of 0.15 rad as subtended by the subject's eye. 'And, as Gibbs (Ref. 34, p. 387) notes: "As gain increased from 0.15 through the range of 0.90, the extent of limb movement required for a given display movement was reduced."

The interaction of gains and lags was clearly shown by the data, and could be expressed by the following equation:

$$T = 0.91 - \frac{0.02}{G} + 1.212L - \frac{0.106L}{G} - 0.4L^2 + \frac{0.032L}{G^2} - \frac{0.003L^2}{G} \quad (7)$$

where T = mean time to make corrective movements
G = system gain (0.15 to 0.90)
L = exponential lag (0.08 to 2.00 sec)

and assuming no differential limb effects of any significant magnitude.

Converting to C/D ratio as the reciprocal of gain:

$$\text{Optimal C/D ratio} = \frac{0.31}{L} + 1.66 + 0.05L \quad (8)$$

The data clearly show that the optimal C/D ratio is a function of time delay (Fig. 9).

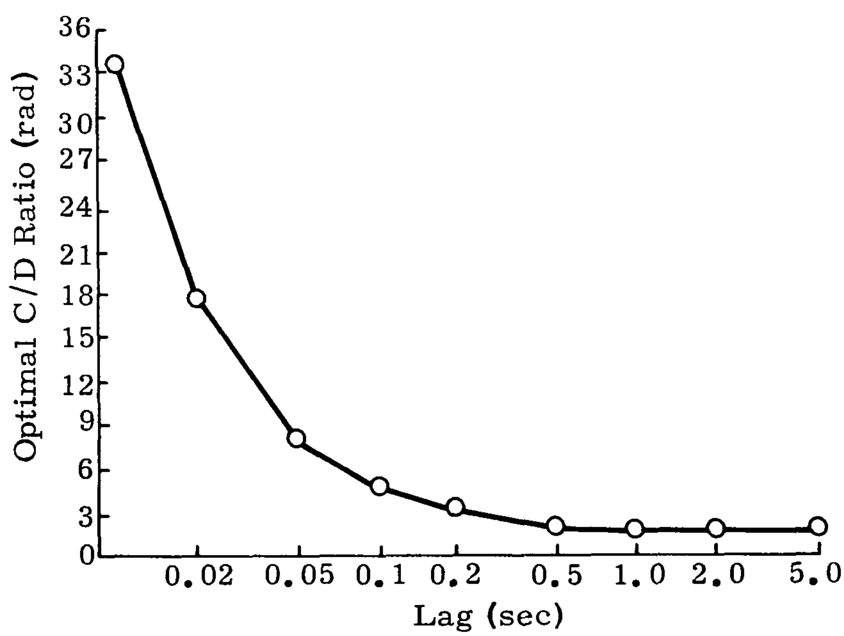

Fig. 9. Optimal C/D Ratio (rad) As a Function of Exponential Time Delay, Position Control (ref 34, p 393)

Velocity control. With the velocity control system, the same exponential time delays were used (0, 0.08, 0.20, 0.50, and 2.00 sec), but with seven gain values ". . . so that the controlled [display] spot moved at rates of 0.4, 0.5, 0.8, 1.0, 3.0, and 4.0 rad/sec, subtended at the subject's eyes, in response to one radian of joystick movement." (Ref. 34, p. 396).

The mean time scores for all limbs showed similar U-shaped curves as a function of gain, invariant in shape with respect to lag. The following expression held:

$$T = 0.949 + 0.255G + 0.444G \tag{9}$$

and the optimal gain for all limbs and lags was found to be 1:3. Individual differences between subjects were far more pronounced than was the case in position control.

3. Warrick (Ref. 38). The first study to suggest the importance of the forcing function variable was that of Warrick (Ref. 38). Using a compensatory tracking task, Warrick introduced the following system variables: (1) exponential lag (5, 105, and 205 ms); (2) forcing function frequency (1/3, 1/4, and 1/5 cps); and (3) control gear ratio (15°, 45° and 65°/15 mm) where gear ratio was defined "... 15°, 45°, and 65° control rotation per 15 mm display pointer movement" (Ref. 38, p. 2). The control was a rotary knob.

Analysis of the data showed significant interactions between forcing function frequency and gear ratio and forcing function frequency and control system lags, the latter suggesting that with increased frequency the determental lag effect was magnified.

4. Wortz, McTee, and Cole (Ref. 39). A second major variable with respect to information display was introduced by Wortz, McTee, and Cole in comparing pursuit and compensatory tracking in interaction with exponential lags (0, 0.25 and 0.50 sec), forcing function variations in terms of display target movement rates (0.28, 0.14 ips, and step function), and four variations in the form of the control-display "displacement functions." A small side-control stick was used.

All variables were found to affect performance levels although no significant interactions were found, according to the authors.* Increased lag decreased performance levels, as might be expected. Pursuit was consistently

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* A complete analysis of variance was not performed. The total analysis matrix was divided into four separate parts. Accordingly, no direct tests of higher order interactions were made.

superior to compensatory tracking. Even under the limitations of the analysis, the failure to find any significant interactions is in curious, and unexplained, contradiction to the other literature.

5. Feddersen (Ref. 40). As Gibbs (Ref. 34, pp. 398-399) points out, gain and lag should differentially affect performance, alone or combined. Alone, high levels of gain and lag should decrease performance. Together, they could be complementary ". . . since an increase of lag may filter the undesirable effects of limb tremor resulting from high gain, and increasing gain may compensate for reduction of display speed caused by lag" (Ref. 34, pp. 398-399). Rockway's (Ref. 37) data supports the concept of reciprocal action (see Fig. 8). Feddersen (Ref. 40) has provided additional evidence, but he suggests that the key causal variable is the rate of display movement achieved by various combinations of C/D ratio and lag rather than by these variables directly.

The task was single-dimension compensatory tracking with side-mounted joystick control. The forcing function was a "random" pattern simulating airborne low level gust phenomena. "Pitch" or vertical control and "roll" or horizontal control were studied in two separate experiments.

Six exponential delay values (0.167, 0.25, 0.5, 0.667, 1.0, and 2.0 sec) were selectively combined with six C/D ratio conditions (1:5, 1:1, 1:1.5, 1:2, 1:4, and 1:6) for the first experiment on "pitch" control. In the second experiment--"roll" control--six exponential time constants (0.111, 0.143, 0.20, 0.33, 0.5, and 1 sec) were selectively combined with six C/D ratio conditions (0.5:1, 0.5:2, 0.5:3, 0.5:5, 0.5:7, 0.5:9). In both experiments, combinations of C/D ratio and lag were created to achieve, in all cases, an equivalent rate of display movement. Despite the wide variations in C/D ratio and lag, performance levels were equal for all conditions in both experiments.

A second replication of both experiments was performed changing only the form of the controlled element response from negatively accelerated (e.g., Fig. 1) to positively accelerated functions. In this case, performance levels were not invariant with equated rate of display movement. Performance increased with higher C/D ratios, and decreased with increasing gain although the rate of display movement was held constant.

These results confirm directly the hypothesis of Gibbs (Ref. 34) that the combined effects of lag and C/D ratio can facilitate performance levels with negatively accelerated controlled element response, and strongly suggests the importance of the rate of display movement variable. With positively accelerated functions, however, the relationship does not appear to hold, and under all conditions, performance levels were inferior to those obtained where the function was negatively accelerated. Wortz, McTee and Cole (Ref. 39) also found the positively accelerated function to produce significantly poorer performance than the negatively accelerated function.

C. Exponential and Sigmoid Functions

Thus, both the data of Feddersen (Ref. 40) and Wortz, McTee and Cole (Ref. 39) appear to point directly at the critical importance of the particular form of the controlled element response. Conklin (Refs. 26 and 27) has provided direct evidence in his experimental comparison of exponential and sigmoid delays.

The initial study (Ref. 26) introduced several variables in a basic tracking situation: (1) exponential versus sigmoid response, (2) time constants of 0.25, 1.00, 4.00, and 16.00 sec, (3) pursuit versus compensatory tracking, and (4) forcing function variations of a random signal and three harmonic signals of π, $\pi + 2/3\,\pi$, $\pi + 2/3\,\pi + 1/6\,\pi$ rad per sec. A horizontal lever provided the control.

In summary, tracking proficiency decreased with increased lag for both compensatory and pursuit tracking. Performance with the sigmoid response was in every case inferior to the exponential form (a finding also reported in Ref. 39). The effect of target course frequency was direct with no significant interactions (except with subjects under compensatory display); the more predictable the course the higher the performance level. The major significant interaction effect was between exponential-sigmoid response and lags. Under equated conditions of lag and forcing function, pursuit was always superior to compensatory tracking.

The second study (Ref. 27) introduced the same experimental variables except that the range of time constant delay terms were restricted to 0, 0.2, 0.4, 0.6, 0.8, and 1.0 sec. Over this range, tracking performance showed a linear decrease (supporting Levine's contention) over the range of time constants from 0.2 to 1.0 sec. Performance was again superior with the pursuit task and exponential function as opposed to compensatory tracking and the sigmoid response form.

D. Oscillatory Transients

In Section II, evidence was cited on short period oscillatory transient effects in compensatory tracking (Refs. 25 and 28). These are quite rapid response effects. Additional evidence (Ref. 29), has been collected for long period oscillatory transients in compensatory tracking with period values of 18, 35, and 71 sec and damping values of 17, 33, and 66 sec (time to damp to half amplitude).

The initial study (Ref. 29, I) showed that damping variations had no differential effect on tracking performance. Performance was equivalent for the 18 and 35 sec period conditions, but at 71 sec performance dropped markedly (in many cases below the level that could have been obtained if the operator had done nothing at all). A priori predictions to the contrary, there are apparently systems of this type so slow in response that the operator cannot control them.

In the second set of studies, control gain was introduced as the main experimental variable (Ref. 29, II). Doubling the control gain (i.e., doubling the C/D ratio) resulted in fully compensating for the lag effect at 71 sec. Performance was essentially equivalent for all high gain conditions (period = 18 and 71 sec; damping = 17 and 66 sec). The reciprocal effects of gain and period-damping variations were clearly shown when control gain was changed over period and damping conditions to equate the controlled element response over an initial 0.5 sec response to the operator's controlled movement. After a short training session, equivalent performance levels were achieved under period values of 18, 35 and 71 sec.

The final set of studies (Ref. 29, III) concerned the nature of the forcing function. In all previous studies, a simple sine wave of 6 cpm had been used. For comparison, a complex function (3 and 6 cpm) was compared with the simple sine wave. Surprisingly, no differential performance effect was found across period values. The second change made was to double the amplitude of the simple sine wave forcing function from ± 0.3 to ± 0.6 inch. The effect on performance was striking. Performance under 35- and 71-sec period conditions was reduced to a "chance" level with no evidence of any learning over 30 trials. Performance with the 18-sec period condition was reduced in half as compared with the low amplitude forcing function value. Increasing the amplitude of the forcing function increased the average control movement extent and apparently elicited transients difficult if not impossible to control.

E. Environmental Variables: Acceleration

Only one study appears in the literature on the combined effects of environmental variables and control system lags. Kaehler (Ref.36), using the University of Southern California human centrifuge, imposed transverse acclerations of 3 and 6 g on 35 subjects who were required to perform a two-dimensional compensatory tracking task.* Forcing functions were complex wave forms ". . . approximating a high performance aircraft in turbulent conditions" (Ref. 36, p. 6). A right-hand side controller was used. The controlled element dynamics were exponential lags with time constants of 0.1, 1.0, and 2.0 sec.

As expected, a systematic increment in performance error for all lag conditions was found with 3- and 6-g loads as compared with performance in a static (1-g) environment. An unexpected result concerned the effect of the lag time constant. In the data cited previously for exponential lags (Refs. 24, 27, and 40), a linear decreasing function was found between performance and increasing lag time constants. Kaehler, however, reports that, for pitch control,

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*Kaehler's study is the only experiment in this literature using a two-dimensional tracking task. All other studies were single dimension.

error decreased as the time constant increased. For roll control, a U-shaped function was obtained with the 1.0-sec lag showing less error then either 0.1 or 2.0 sec time constants. Apparently, in this case at least, exponential lag aided tracking performance. Kaehler (Ref. 36, pp. 26-27) comments that this may be a case of lag reducing the effects of high control gain. Kaehler's data summary is shown in Fig. 10.

F. Procedural Variables: Transfer of Training

As noted previously, a number of critical variables in human tracking performance concern those procedural variables specific to the human operator. One such class is that of transfer of training where the objective is to discover the effect of learning by the operator of one task upon the subsequent learning of another. Among other items of interest, transfer is fundamental to the design of training devices and for extrapolating results obtained through simulation to operational performance.

1. Exponential lags. A study by Levine (Ref. 40) effectively illustrates transfer effects with exponential control system lags. With a one-dimensional compensatory tracking task, Levine inserted exponential delays with time constants of 0.015, 0.150, 0.900, 2.10 and 3.00 sec. Two studies were performed. In the first experiment, 50 subjects were trained on the 3.00 sec delay. They were then divided into groups of ten each and given subsequent training with delays of 0.015, 0.150, 0.900, 2.10 and 3.00 (the latter control group a continuation of original learning). For error and time on target scores, transfer performance of all groups was essentially equal.

In the second experiment, the procedure was reversed: 30 subjects in groups of ten were trained on the 0.015, 0.900, and 3.0 sec delays and then subsequently trained on the 0.015 sec lag. On transfer trials, the three groups performed quite differently. Transfer was found to decrease with decreasing similarity between the training and transfer situations.

2. Oscillatory transients. In the studies cited previously (Ref. 29) on the effect of oscillatory transients, a major concern was with transfer of training across various long period values. The findings were:

(1) For optimum transfer, the period values of the transients should be as close as possible between training and transfer conditions. Training on the shorter period condition (18 sec) produced interference in the subsequent learning of a longer period condition (35 sec).

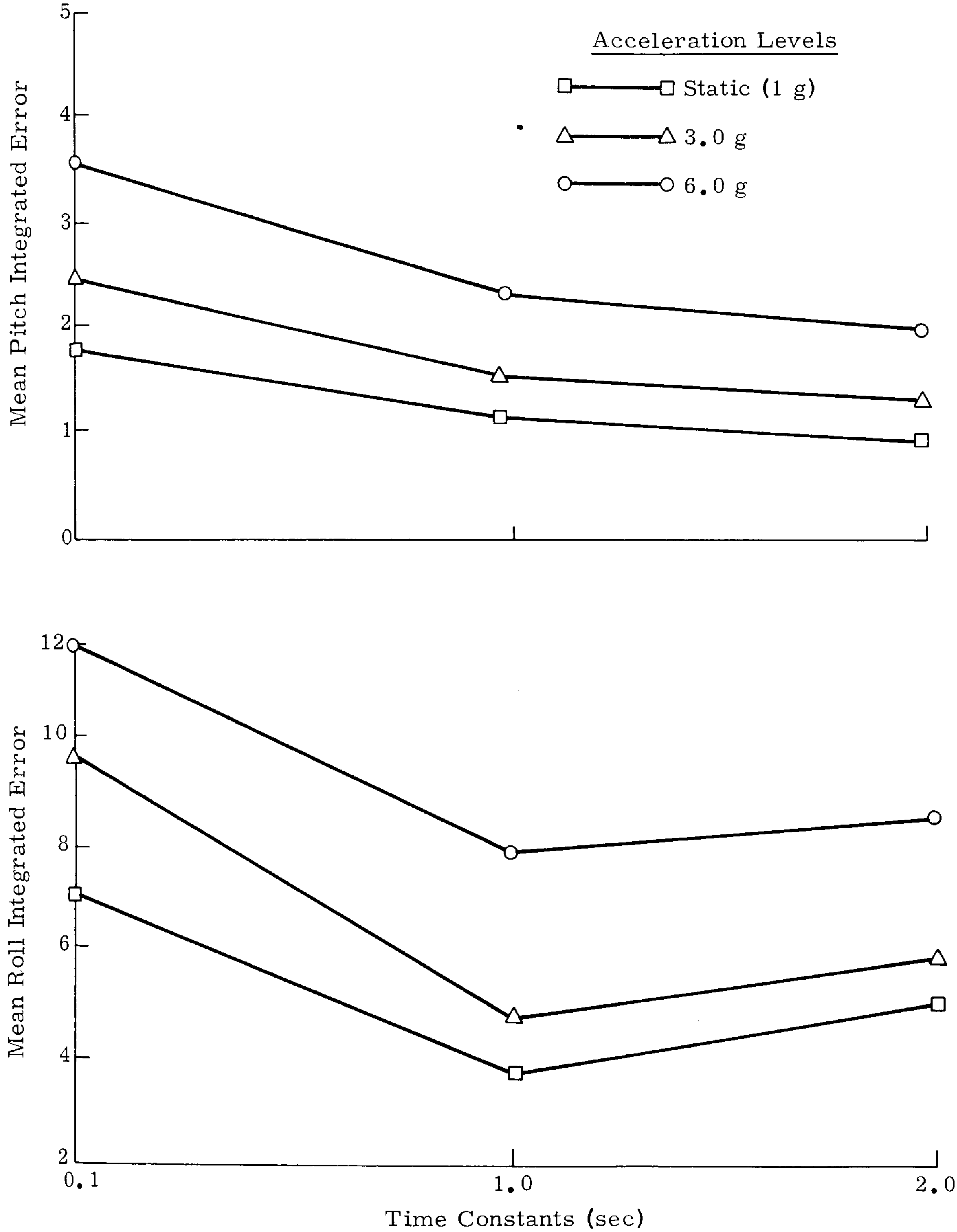

Fig. 10. Tracking Performance As a Function of Acceleration Loads, Exponential Lags, and Operator Control Axis (ref 36, p 20)

(2) Increasing control gain produced uniformly high transfer performance regardless of the original training conditions. With respect to transfer, control gain compensated for differential period effects during original learning. However, given equivalent oscillatory transients, transfer from high to low control gain was strongly negative while transfer from low to high gain was strongly positive.

(3) Increasing forcing function complexity substantially affected transfer of training but not original training performance. Increasing forcing amplitude markedly affected training performance but not transfer of training.

In a sense, transfer of training phenomena are a reflection of the adaptability of the human operator in shifting from one man-machine system configuration to another. Perhaps the best that can be said at the present is that the magnitude and direction of transfer effects in systems containing control system lags are as asymmetric, within the limited cases studied to date. A safer estimate is that transfer effects are not predictable either from the available literature or from current theories of transfer of training.

IV. SUMMARY AND EVALUATION

The objective of the present review was to examine the core literature on the effects of control system lags on manual control system performance. As restricted here, four specific transformations of the controlled element were defined as creating control system lags: transmission, exponential, sigmoid, and oscillatory transient delays. Some comment might be appropriate summarizing a few of the critical findings with respect to each type of lag.

A. Transmission Delays

It is a curious fact that Warrick (Ref. 8) precipitated experimental interest in the control system lag problem, yet his study remains the only systematic research investigation in the literature on transmission-type lags. Considering the critical interaction phenomena between task variables so pronounced in the other lag types, it seems of particular interest for future study to investigate task variable interaction with transmission-type lags. Pure delays of this sort are of particular interest in the applied context with respect to long distance remote control (e.g., Refs. 42 and 43), and further study would appear to be of value. As noted in Section II-B, Warrick found an inverse linear relationship between performance and transmission lag. It would be of interest to see how this relationship is affected, if at all, with variations in such parameters as the forcing function, display modes, and control/display ratio.

B. Exponential Delay

The bulk of the evidence available in this general area concerns the effect of exponential delays on tracking and discrete operator performance. As might be expected, this literature is not entirely consistent, but certain very strong trends do occur.

(1) The importance of interaction effects with other task variables seems firmly established. This inference, coupled with the functional data of Kaehler (Ref. 36), suggests that the equations of Levine (Ref. 23) and Gibbs (Ref. 34) must be applied with caution.

(2) Display/control ratio--or "gain"--is clearly one of the most significant variables in determining the effects of exponential delay. There seems to be little question that the concept of Gibbs (Ref. 34) on the reciprocal action of gain and lag is essentially correct. The specific formal relationships developed by Gibbs, however, were derived from discrete positioning tasks, and empirical verification within the more conventional tracking context would be desirable.

(3) It is difficult to evaluate the specific significance of the forcing function variations. In the broader sense, this relates to the time predictability of the stimulus input sequence, and Garner (Refs. 44 and 45) has stressed some theoretical implications of the interaction between lag and stimulus predictability.

(4) In these studies, pursuit tracking was invariably superior to compensatory tracking. Other evidence (Refs. 31 and 32) now suggests that for certain forcing functions the reverse may hold. A possible second order interaction may exist between display modes, forcing function frequency, and exponential lag. While all these variables were studied by Wortz, McTee and Cole (Ref. 39) and Conklin (Refs. 26 and 27), incomplete data analysis restrains any conclusions.

(5) The evidence of Kaehler and Rockway (Refs. 36 and 37) directly suggests that under certain system conditions exponential delay may in fact be desirable for system control. Further study to delimit precisely these conditions would seem desirable.

C. Sigmoid Delay

The studies of Conklin (Refs. 26 and 27), Feddersen (Ref. 40), and Wortz, McTee and Cole (Ref. 39) strongly imply that sigmoid delay introduces either marginal control or certainly performance inferior to exponential delay treatments. In the Conklin study, sigmoid delay resulted, in some cases, in performance levels worse than chance. That is, the operator's performance score was less than if he had done nothing at all. While on the whole the human operator is a uniquely superior servomechanism, he can, given the chance, be a very bad system controller. In comparing exponential with sigmoid delay, there is at least a superficial relationship with the general finding of the relative superiority of velocity control over acceleration manual control systems.

D. Oscillatory Transients

Control by the operator of control system oscillatory transients presents a far more difficult manual control problem even when stable transients are employed. That difficulty should increase significantly if marginally stable or unstable transients were imposed. A number of possible effects might be hypothesized in general as the task difficulty of a manual control system is increased. First, operator variability should increase markedly, and, further, individual differences in response to task variable manipulation should become greater. Second, it is possible that as task difficulty increases, task variable interaction phenomena may become more pronounced. At the present time, however, these suspicions are not supported by any direct evidence although they are testable through future experimentation.

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